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Measurement of the condensation rate of vapor bubbles rising upward in subcooled water by using two ultrasonic frequencies

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ABSTRACT

The condensation rate of vapor bubbles, defined by $v_c = -dR/dt$ where R is the spherical-equivalent bubble radius, t is time, is an important parameter to determine the interfacial-condensation heat and mass transfer in subcooled boiling. Previous measurements of the condensation rate were mainly based on the optical visualization. In the paper, the development of a new method that uses two ultrasonic frequencies for the measurement of the condensation rate in subcooled boiling is presented. The ultrasonic velocity profile (UVP) method is used for the velocity measurement. Two simultaneous UVP measurements by the two frequencies are exploited. The principle of the new condensation-rate-measurement method is established. In the method, the UVP data of the bubble surface velocity are used. In subcooled boiling, the bubble-surface velocity is affected by the condensation. The UVP measurement must capture correctly the condensation effect on the bubble-surface velocity. In order to confirm the applicability of the UVP method to the measurement of the surface velocity in this case, the growth rate of air bubbles from a nozzle submerged in water is measured and compared with the result of optical visualization and digital image processing. Such growth process is analogous to that of vapor bubbles in a boiling process, and it is the inverse of the condensation process. Evaluation of the new condensation-rate-measurement method is carried out by the measurements of adiabatic air–water-bubbly column and subcooled pool boiling in vertical round tube.

1. Introduction

Boiling bubbly flow is widely used in many industrial and engineering applications [1,2]. Subcooled boiling occurs when the bulk liquid is below saturation. At the same time, the liquid at the vicinity of the heated wall is boiling. Vapor bubbles are generated. The detached vapor bubbles enter the bulk liquid and condense [3–5].

The condensation rate of vapor bubbles is defined by $v_c = -dR/dt$ where R is the spherical-equivalent bubble radius and t is time (e.g. see [6]). It is an important parameter in the study of subcooled boiling. An example is the analysis of the interfacial condensation heat transfer (e.g. see [7]). The condensation rate determines the heat and mass transfer between the vapor and liquid phases (e.g. see [8,9]). In a boiling channel, the condensation interfacial heat transfer coefficient affects the location of the onset of the significant void (OSV) where the void fraction sharply increases [10]. In numerical simulation based on the two-fluid model, the condensation rate directly appears in the source-sink terms of the continuity equations of the liquid and vapor phases, and also in the momentum and energy equations (e.g. see [11]). The averaging of the equations requires that mechanistic models are used to simulate the condensation rate. Consequently, experimental measurements are highly important to develop such closure models.

Previous experimental investigations of subcooled boiling mainly exploited the optical visualization methods [10,12–16]. Less widely used methods would include the interferogram [14], the wire mesh tomography [17] etc. The optical and interferogram methods require specially-designed viewing windows that can be highly challenging in the high temperature and/or pressure conditions [13]. Measurements were mainly carried out for either single or a limited number of bubbles in order to avoid the bubble overlapping in the flow images. The wire mesh tomography [17]

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Nomenclature

c	sound speed in the working liquid, m/s
d_1, d_2	major and minor axes of the ellipse in the first image of an image pairs, mm
d'_1, d'_2	major and minor axes of the ellipse in the second image of an image pairs, mm
D_b	spherical-equivalent bubble diameter, m
Δt	time difference between the two images of an image pair, s
f_0	ultrasonic center frequency, MHz
f_{01}	ultrasonic center frequency of the sensor TDX1, MHz
f_{02}	ultrasonic center frequency of the sensor TDX2, MHz
f_{d}	Doppler shift frequency, Hz
F_{prf}	ultrasonic pulse repetition frequency, Hz
h_c	interfacial condensation heat transfer coefficient, W/m^{2}K
h_{fg}	latent heat of vaporization, J/kg
I.D.	inner diameter of pipe, nozzle etc., mm
Ja	Jakob number, –
k_f	thermal conductivity of water, W/mK
$L_{\max}$	maximum measurable depth, m
λ_0	wave length of the emitted ultrasonic pulses, mm
N	number of the wave cycles of the emitted ultrasonic pulses, –
N_{bubble}	number of the vapor bubbles used to calculate the averaged condensation rate by the optical method, –
Nu_c	interfacial condensation Nusselt number, –
Pr_f	Prandtl number of water, –
R	bubble radius, m
Re_b	bubble Reynolds number, –
ρ_v	vapor density, kg/m^3
θ	inclined angle between the ultrasonic-sensor axis and the main flow direction, °
τ	travelling time of the ultrasound from the sensor to the measurement channel x_n and back to the sensor, s
t	time, s
t_1, t_2	two time instances of the image pairs of a bubble, s
t_{emit}	time origin of the emission of an ultrasonic pulse, s
t_{sample}	difference between the sampling-time instance and the time origin t_{emit}, s
T_{sub}	degree of liquid subcooling, K
V_B	bubble rising velocity (i.e. bubble centroid velocity), m/s
$\overline{V_b}$	time average of the bubble rising velocity, m/s
v_c	condensation rate (or condensation velocity) of bubbles, m/s
$v_{c(\mathrm{optical})}$	condensation rate of a bubble calculated by the optical method, m/s
$\overline{v_c}$	time average condensation rate of bubbles along the ultrasonic measurement line, m/s
$\overline{v_{c(\mathrm{optical})}}$	time average condensation rate of bubbles in the test section (by using optical method), m/s
$v_{\max}$	maximum measurable velocity, m/s
V_{TDX1}	measured velocity by the sensor TDX1, m/s
$\overline{V_{\mathrm{TDX1}}}$	time average of the measured velocity by the sensor TDX1, m/s
V_{TDX2}	measured velocity by the sensor TDX2, m/s
$\overline{V_{\mathrm{TDX2}}}$	time average of the measured velocity by the sensor TDX2, m/s
v_{x_n}	fluid velocity at the measurement channel x_n, m/s
w	spatial resolution of the UVP method, mm
x_0, x_n	location of the measurement channels numbered 0 and n, m
X_1, Y_1	co-ordinates of the bubble center at $t = t_1$, m
X_2, Y_2	co-ordinates of the bubble center at $t = t_2$, m

can be applied to high void fraction two-phase flow. However, it is an intrusive method. The intrusive effects (e.g. on the flow behaviors, measured data etc.) must be carefully investigated. Hence the development of new methods for the measurement of boiling phenomena is needed.

The UVP method has been established as a powerful tool for the visualization of the spatio-temporal velocity distribution of liquid flows [18]. In the UVP method, an ultrasonic sensor is used to emit ultrasound and receive the echo signal back scattered from the flow field. Velocity distribution along the sound path is calculated by analyzing the received echo signal. Since ultrasound can transmit through various material, no optical window is required. Non-intrusive measurements, applications of the method to existing systems and to those in operation etc. are enabled. Measurement of extreme industrial conditions (such as high temperature, pressure etc.) can be possible. Therefore, application of the UVP method to two-phase flow measurement has attracted lots of research efforts.

Aritomi et al. [19] was the first to apply the UVP method to the measurement of the air–water bubbly flow in a vertical channel. Measurements of boiling bubbly flow have also been investigated [20–22]. Applications of the method to high temperature conditions have also been performed (e.g. see [23]). Besides, the multi-wave UVP method has been developed [24] to measure the velocity profiles of liquid and those of bubbles simultaneously along one measurement line. The signal processing techniques used in the UVP method were either the pulsed Doppler [24] or the ultrasonic time domain cross correlation (UTDC) technique [25]. Therefore, the method can be useful for the measurement of subcooled boiling.

In the present paper, the development of a new method to measure the condensation rate of vapor bubbles rising upward in subcooled water is presented. The method utilizes two ultrasonic frequencies to measure the velocity of the top and bottom surfaces of condensing vapor bubbles. Such velocities are the sum of the bubble rising velocity and the condensation rate at the surface. A technique to calculate the condensation rate from the two measured velocities is established. Two ultrasonic sensors (or two simultaneous UVP measurements) are exploited to measure the two velocities. The inclined angle of the sensors is set different. One sensor is fixed in the downward direction to measure the velocity of bubble's top surface. The other one looks upwards to measure the velocity of the bubble's bottom surface. Then the condensation rate is calculated via the difference between the velocity of the bubble top- and bottom surfaces. In this method, the change caused by the condensation to the surface velocity needs to be captured with high accuracy. Therefore, the resolution of the measurement by each frequency must be sufficient to capture the velocity change. Investigations were carried out to measure the surface velocity of air bubbles from a nozzle submerged in still water. The data obtained by the UVP method is compared with that of the high spatial–temporal optical visualization which uses a high speed camera. The agreement between the two measured data shows that the UVP method is suitable for the condensation-rate measurement. That is because the growth of air bubbles from a nozzle in water is analogous to that of vapor bubbles in superheated liquids [26–28]. Together with that, the growth of vapor bubbles is the inverse of the condensation in the subcooled boiling [28]. In the next step, the new method is first evaluated by the measurement of the adiabatic air–water bubbly column in a verti-